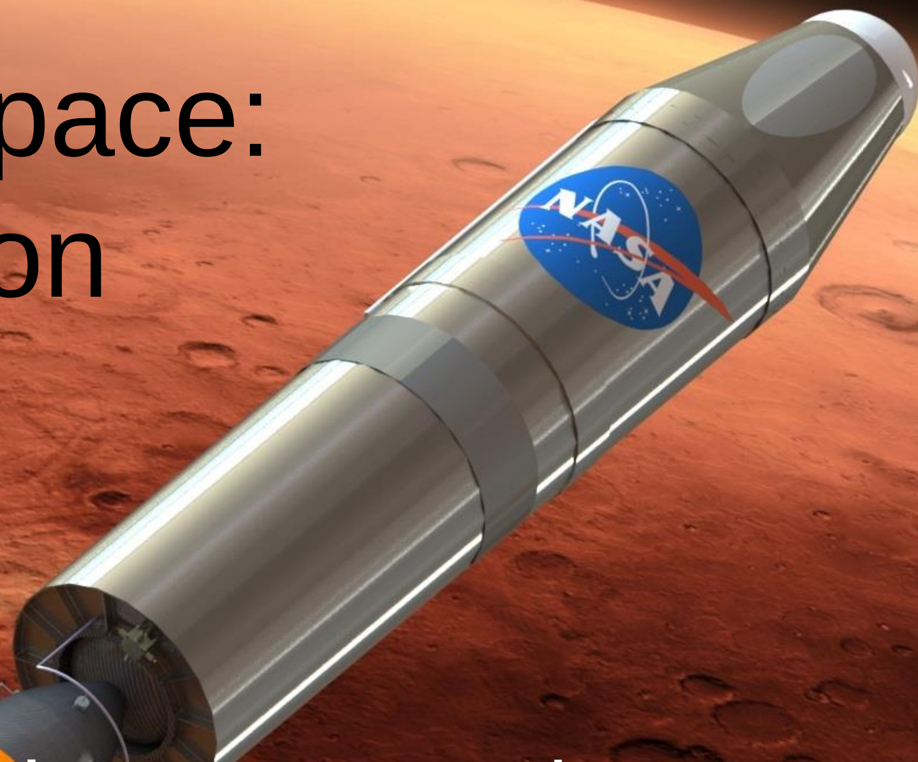
# Surviving Space: Propulsion




Ashley C. Karp, PhD

Jet Propulsion Laboratory, California Institute of Technology

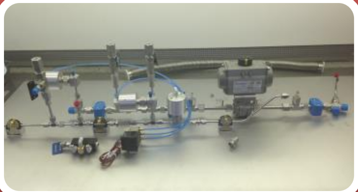
Stanford AA 108N Lecture

23 Jan 2018

# Surviving Space: Propulsion

- Propulsion – how you get where you're going.

Propulsion Imparts loads on spacecraft



Components must be designed to survive environment

Test like you fly

# My Path to JPL

## A.B./B.A. in Astrophysics, Physics Political Science, ‘05

- Majors: astrophysics, physics, political science
- Research: Infrared Spatial Interferometer
  - Prof. Charles Townes

## Ph.D. in Aeronautics and Astronautics, ‘12 (and M.S. ‘09)

- Thesis: An Investigation of Liquefying Hybrid Rocket Fuels with Applications to Solar System Exploration
  - Profs. Brian Cantwell & Scott Hubbard
  - Two summer internships at JPL (’08, ‘11)

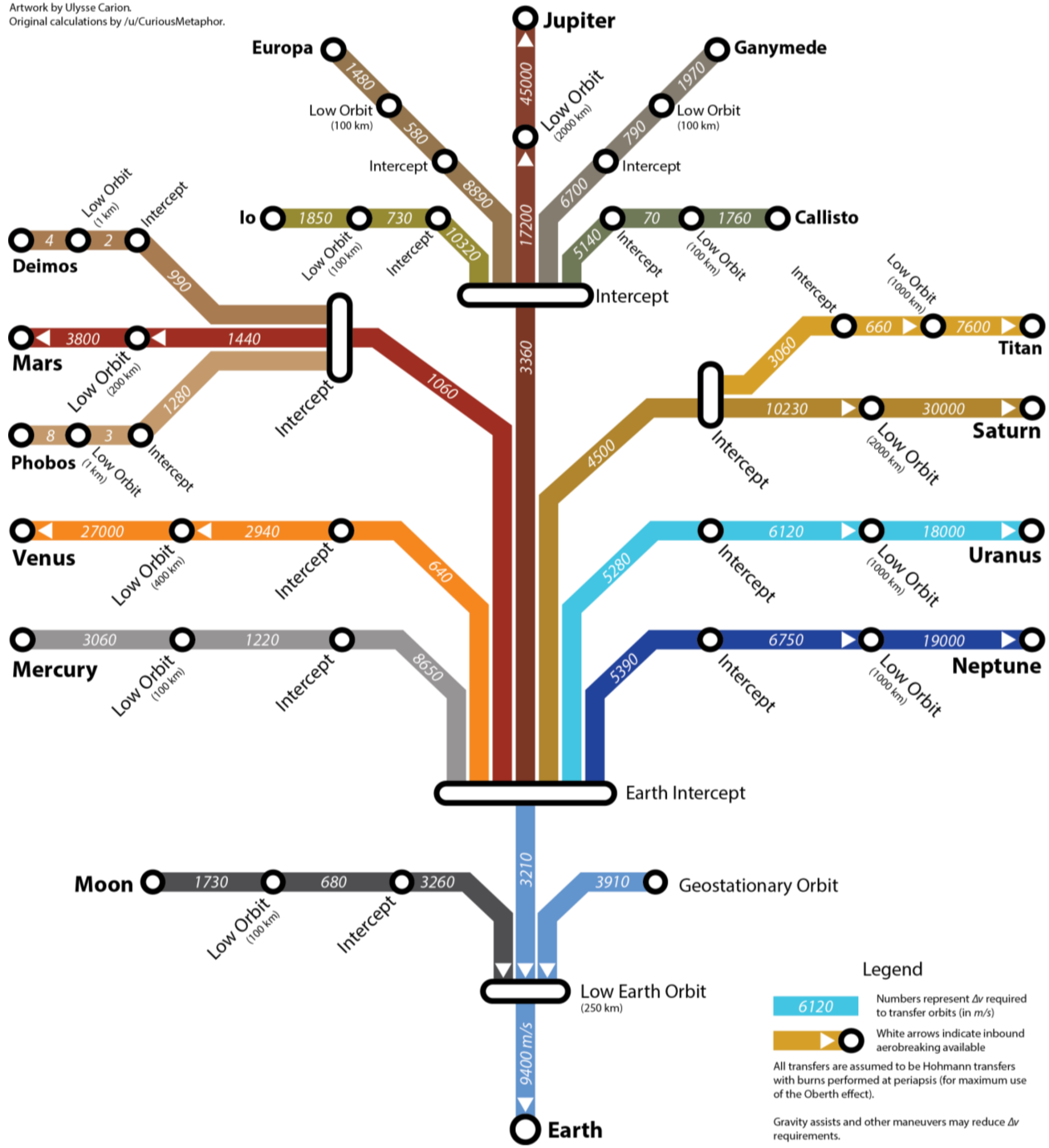
# What does a Propulsion Engineer do?

Image: NASA

# Delta-V (ΔV)

Changing velocity allows you to change or escape orbit. It's how we move around in space.

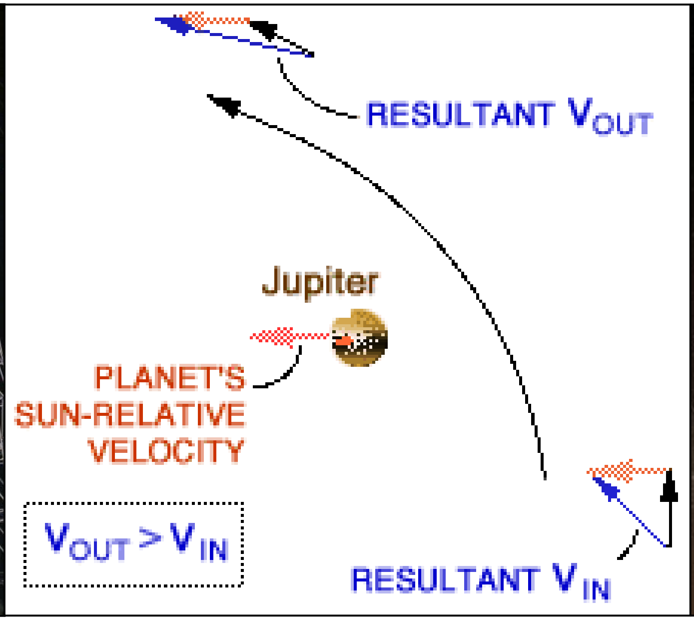
Cartoon Subway map of the solar system



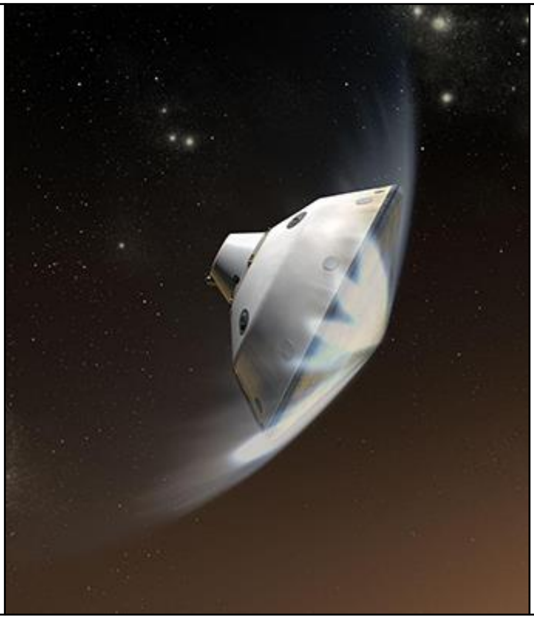
# Examples of how to get ΔV

Rockets

Gravity Assist



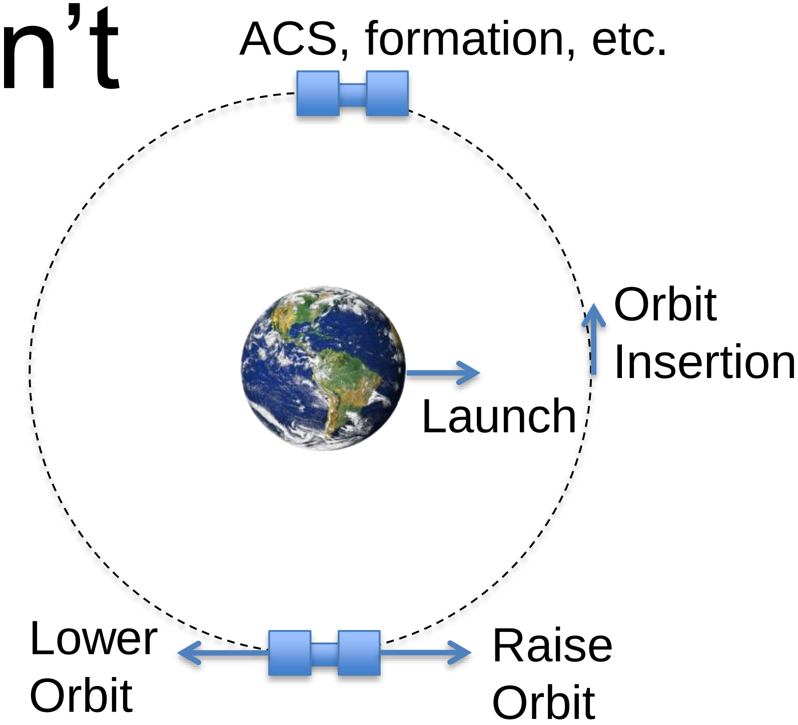

Aerodynamics (Drag)



Solar Sails

Disclaimer: not a comprehensive list

# $\Delta$V con’t

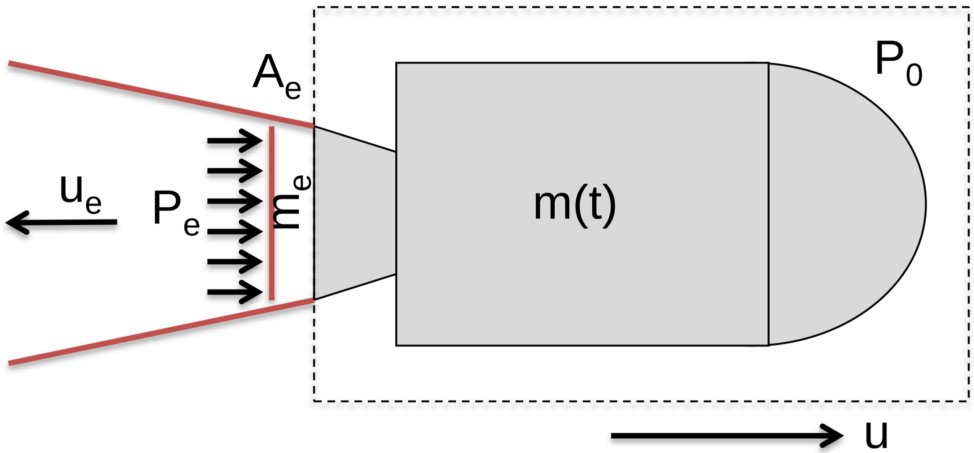



- Primary
  - Launch
  - Orbit Insertion
  - Orbit Change
  - Descent/Landing
- Secondary
  - Attitude Control (ACS)
  - Station Keeping
  - Formation Flying

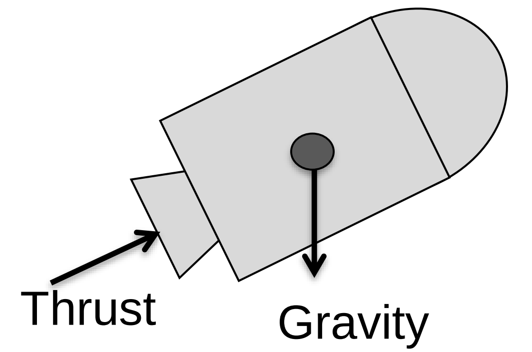
Use for both up and down.

New Shepherd, Blue Origin

# Newton's Second Law




*Neglect aerodynamic forces for now




$$\Sigma F = \frac{dp}{dt}$$

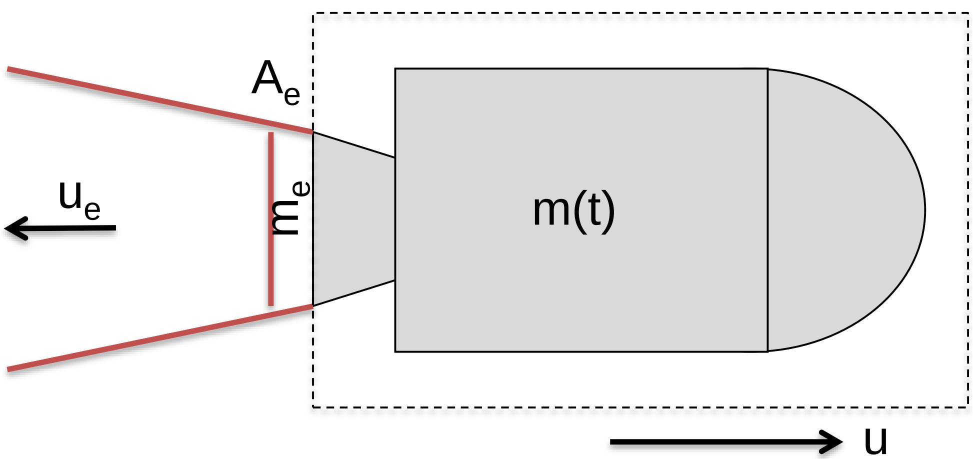
$$\Sigma F = (p_e - p_o)A_e - mg_0 \cos\theta$$

$$\frac{dp}{dt} = \frac{d(mu)}{dt} + \frac{dm_e}{dt}(u + u_e)$$

$$\frac{dp}{dt} = m\frac{du}{dt} - u_e\frac{dm}{dt}$$

# The Rocket Equation

- Derive from conservation of momentum (assume no external forces, perfectly expanded nozzle)




$$\Delta V = Isp\; g_0 \ln\left(\frac{m_i}{m_f}\right)$$

$$\underbrace{u_e = Isp\, g_0}$$

Effective exhaust velocity
Also often called "c"

# Propellant Mass

**Table 14-18. Average Mass by Subsystem as a Percentage of Dry Mass for 4 Types of Spacecraft.** Types include those with no propulsion, those in Low-Earth Orbit with propulsion, those in high-Earth orbit, and planetary missions. See App. A for more information.

Source: Wertz and Larson, The New SMAD

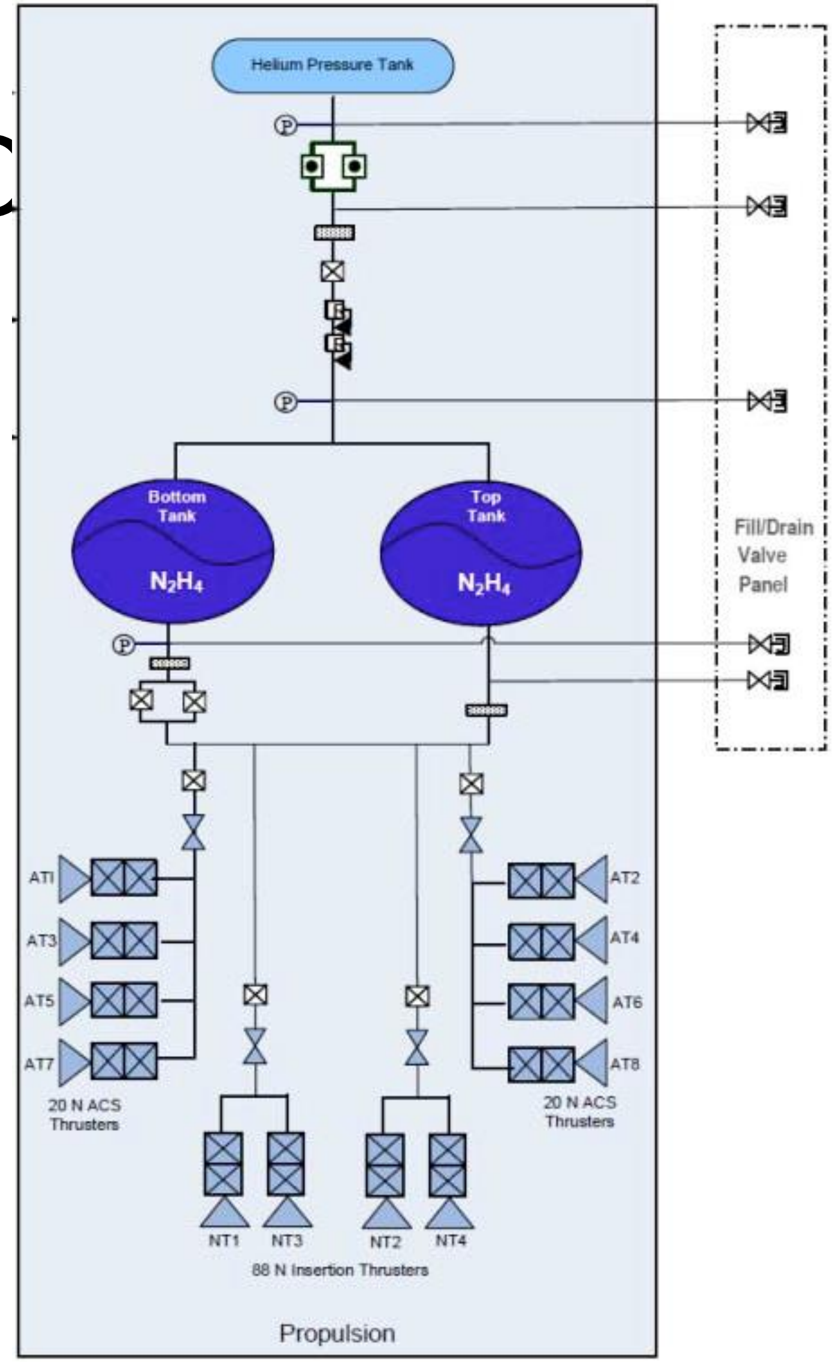
| Subsystem (% of Dry Mass) | No Prop | LEO with Prop | High Earth | Planetary |
|---|---|---|---|---|
| *Payload* | 41% | 31% | 32% | 15% |
| *Structure and Mechanisms* | 20% | 27% | 24% | 25% |
| *Thermal Control* | 2% | 2% | 4% | 6% |
| *Power (incl. harness)* | 19% | 21% | 17% | 21% |
| *TT&C* | 2% | 2% | 4% | 7% |
| *On-Board Processing* | 5% | 5% | 3% | 4% |
| *Attitude Determination and Control* | 8% | 6% | 6% | 6% |
| *Propulsion* | 0% | 3% | 7% | 13% |
| *Other (balance + launch)* | 3% | 3% | 3% | 3% |
| *Total* | 100% | 100% | 100% | 100% |
| *Propellant* | 0% | 27% | 72% | 110% |



Propellant can be a large percentage of spacecraft mass

# Example: LRO

- Lunar Reconnaissance Orbiter
- 4 x 88N Insertion thrusters
- 8 x 20N ACS thrusters




Source: IAC-07-C1.7.06

# Fuel Budget

**Table 14-19. Lunar Reconnaissance Orbiter Fuel Budget at Launch.** (Courtesy of Charles Zakrzwski)

| *Total Launch Mass (kg)* | 1915.27 | | | | | |
|---|---|---|---|---|---|---|
| ***Maneuvers*** | **Delta V (m/s)** | **Effective $I_{SP}$ (s)** | **Total Propellant Used for Maneuver (kg)** | **Delta H Propellant (kg)** | **Total Propellant Used (kg)** | **S/C Mass at End of Burn (kg)** |
| ***MCC Eng*** | 2 | 202 | 1.93 | 0 | 1.93 | 1,913 |
| ***MCC Burn(s)*** | 28 | 202 | 26.85 | 0 | 26.85 | 1,886 |
| ***Thruster Check Out*** | | | | 0 | 0.23 | 1,886 |
| ***LOI Eng*** | 8 | 223.6 | 6.87 | 0 | 6.87 | 1,879 |
| ***LOI – 1*** | 583 | 223.6 | 438.64 | 0 | 438.64 | 1,441 |
| ***LOI – 2-5*** | 362 | 220 | 222.48 | 0 | 222.48 | 1,218 |
| ***MOI – 1*** | 48 | 220 | 26.80 | 0 | 26.80 | 1,191 |
| ***MOI – Others*** | 8 | 217 | 4.47 | 0 | 4.47 | 1,187 |
| ***Station Keeping*** | 162 | 217 | 86.98 | 0 | 86.98 | 1,100 |
| ***Momentum Unloading*** | | Na | | 17 | 17.00 | 1,083 |
| ***Extended Mission*** | 69 | 217 | 34.54 | | 34.54 | 1,048 |
| ***Additional Margin*** | 46 | 217 | 22.41 | 0 | 22.41 | 1,026 |
| ***Totals*** | 1316 | | | | 889.20 | |



Launch mass:
Dry mass (1017.7 kg)
Residuals (5.2 kg)
Helium (3.2 kg)
Tot = 1026 kg

Usable propellant = 889.20 kg

Legend:
MCC – mid-course correction
LOI – lunar orbit insertion
MOI – mission orbit insertion

Source: Wertz and Larson, The New SMAD

# Propulsion Design
## Minimizing Mass

- Considerations
  - Isp or C ($u_e = C = I_{sp}\, g_0$)
  - Dry mass
    - Propulsion system requirements (temperatures, power, plumbing, etc.)
  - Mission requirements
    - Thrust, throttling, multiple burns, etc.

$$\Delta V = Isp\; g_0 \ln\left(\frac{m_i}{m_f}\right)$$

$$\Delta V = Isp\; g_0 \ln\left(\frac{m_L + m_P + m_S}{m_L + m_S}\right)$$

$$m_P = m_f\left(e^{\Delta V / Isp\; g_0} - 1\right)$$

| Prop System | Typical Isp |
|---|---|
| Cold Gas | 70 |
| Monoprop | 240 |
| Biprop (storable) | 320 |
| Biprop (cryogenic) | 450 |
| Solid | 285 |
| Hybrid | 330 |

# Example

- You want to perform a LEO → GEO transfer
  - $\Delta V_{Chem}$ ~ 4 km/s
- Estimate the propellant mass you need for a thruster with Isp ~ 70 s (cold gas), vs. a liquid bipropellant Isp ~ 320 s
  - Assume your final mass is 50 kg (payload plus structure and residuals)
- Which would you use?

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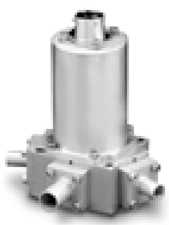
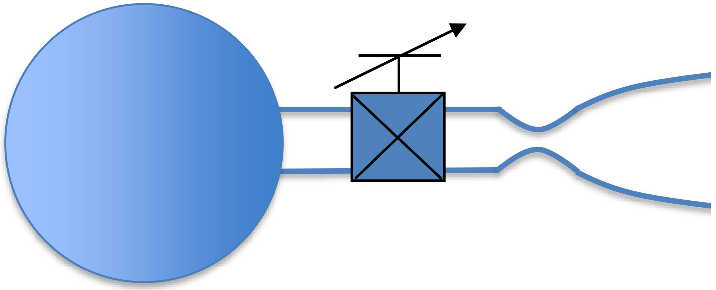
$$\boxed{\Delta V = Isp\, g_0 \ln\left(\frac{m_i}{m_f}\right)}$$

# Types of Chemical Propulsion

| | Cold Gas | Mono-propellant | Bipropellant Liquid | Solid | Hybrid |
|---|---|---|---|---|---|
| Example |  |  |  |  |  |
| | Triad Thruster, Moog | MR-111, Aerojet Rocketdyne | Merlin Engine, SpaceX | Star 48, Orbital ATK | RocketMotor-Two, VirginGalactic |
| Uses | ACS | RCS, ACS, Small Main Engines | Launch, Orbit Insertion | Boosters, Insertion Burns | TBD: Tourism, CubeSats, MAV? |

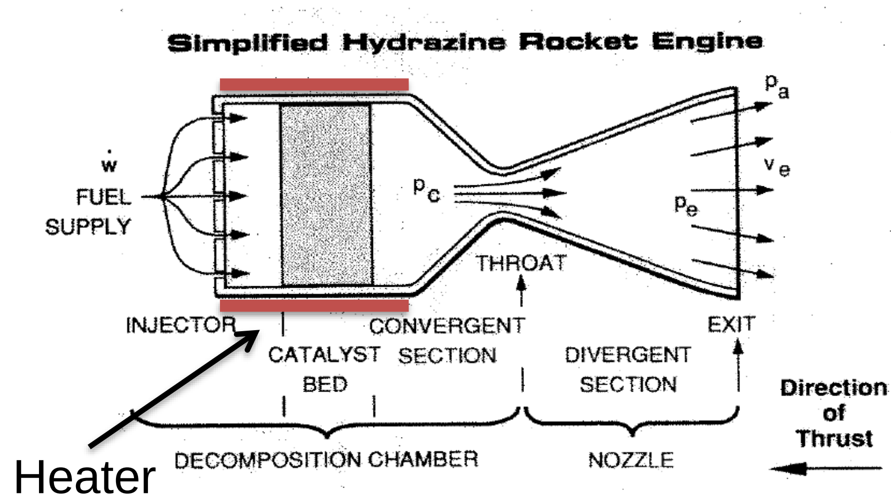
# Cold Gas Thruster

- Pressurized gas expands through a nozzle
- Common propellants:
  - $N_2$, He, Freon, Ammonia
- Advantages
  - Simple
  - Many Commercial Off The Shelf (COTS) components and systems available
  - Propellants are typically safe (non-toxic)
- Disadvantages
  - Low Isp
  - Very sensitive to valve timing
  - Temperature of gas can lead to condensation in the nozzle

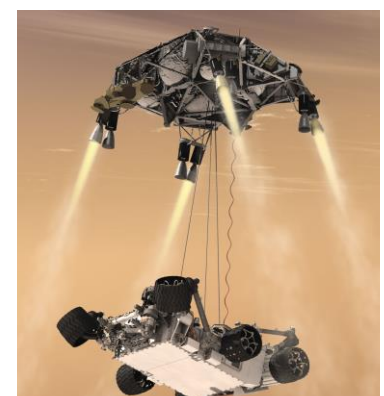


# Monopropellant

- Catalytic decomposition
- Monopropellants:
  - Hydrazine ($N_2H_4$)
  - Nitrous Oxide ($N_2O$)
  - Hydroxylammonium nitrate, HAN ($H_4N_2O_4$)
  - LMP-103 (ammonium dinitramide, ADN)
- Advantages
  - Simple, COTS, easy to throttle
- Disadvantages
  - Catalyst is hard to make and heavy
  - Most propellants are toxic



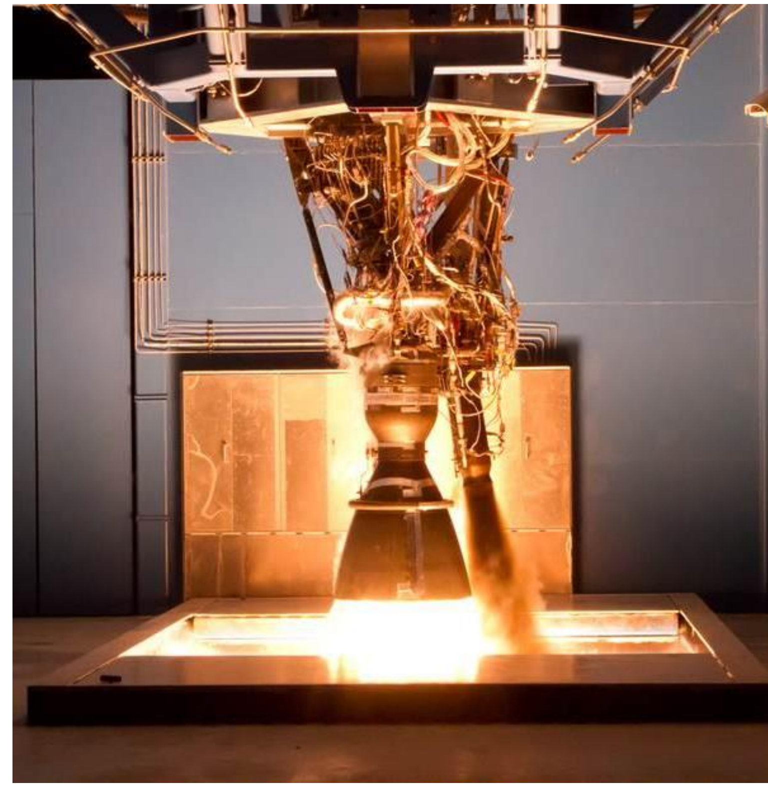

MR-103
1N (0.2 lbf)



MLE's
400-3000N

# Liquid Bipropellant

- Advantages
  - High performance (Isp)
  - Throttleable (but complex)
  - Restartable
- Disadvantages
  - Complex
  - Low Density
  - High performance propellants can be cryogenic



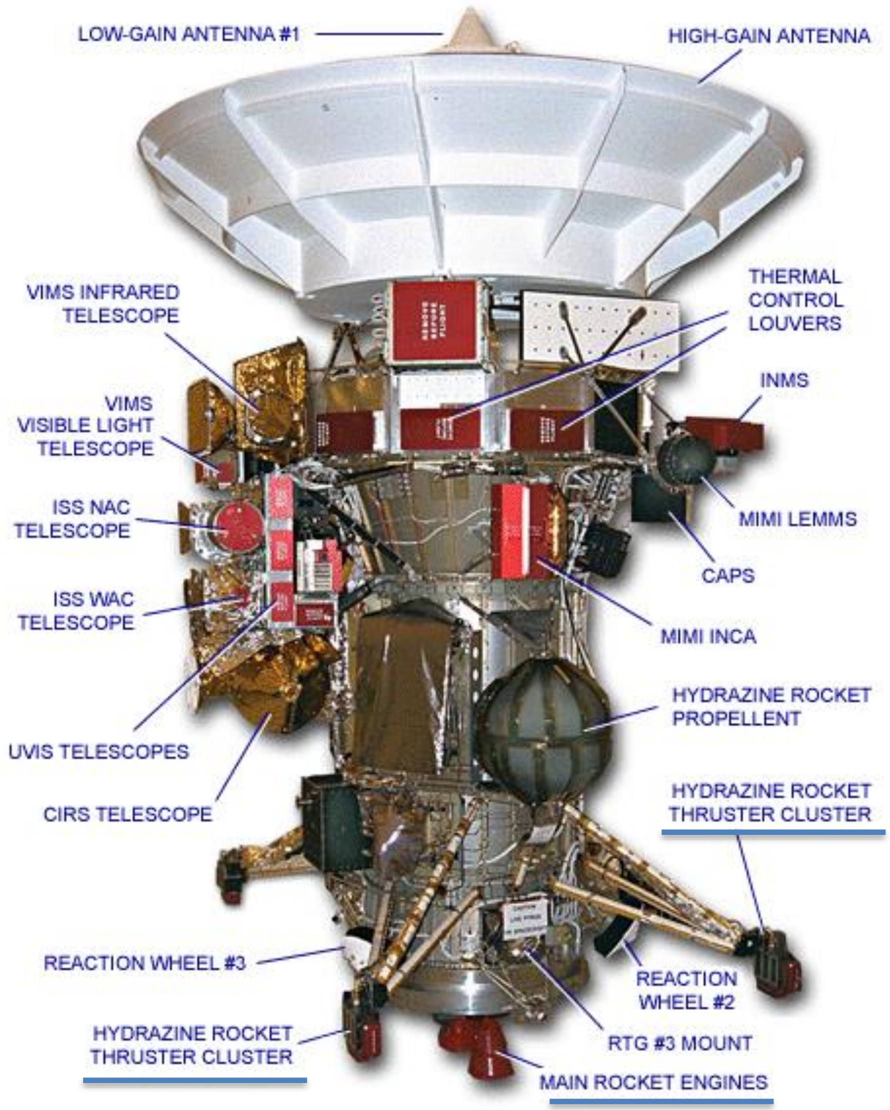
Merlin Engine (845-914kN)

Image Credit: www.SpaceX.com

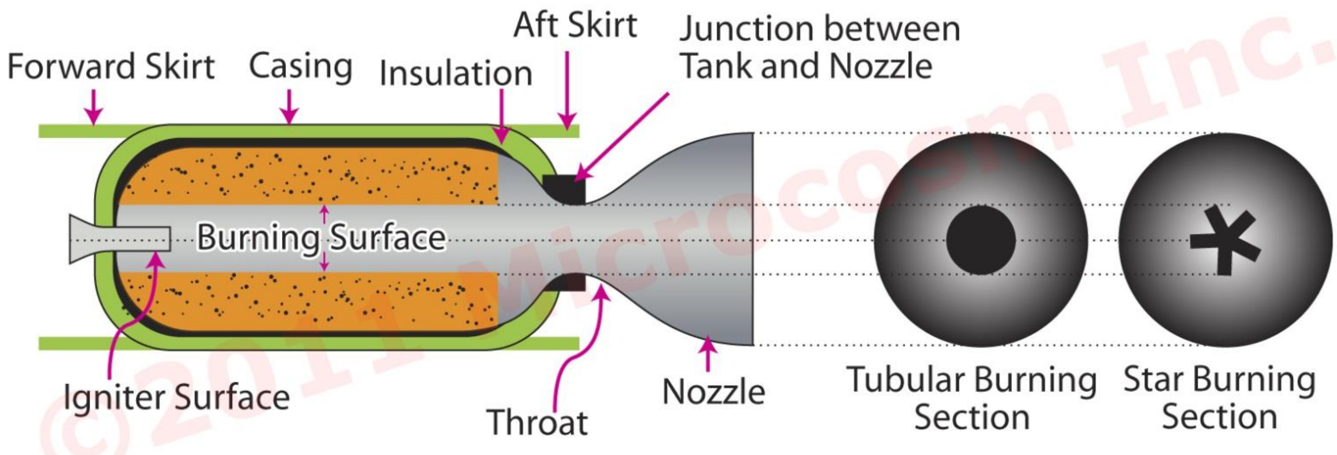
# Example: Cassini (Saturn)

- Cassini-Huygens is a NASA/ESA/ASI mission that was designed to explore the Saturn system, including its rings and moons, with a special focus on Titan. It “plunged” into Saturn last year.
  - It took 6.7 years to get to Saturn
  - Size: 6.8 m tall by 4 m wide
- Wet mass: 5,574 kg
- Main engines are storable biprop
  - MMH/NTO
  - $M_p$ = 3,000 kg
- Hydrazine thrusters
  - Used for 3-axis attitude control and reaction wheel desaturation
  - $M_p$ = 132 kg

What percentage of the total mass is propellant?



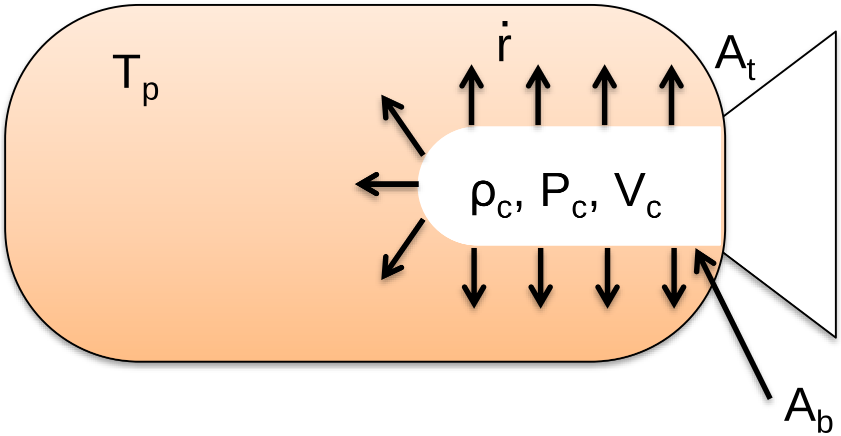
# Solid Rocket Motor




Schematic Drawing of a Nominal Solid Motor

- Advantages:
  - High density propellants
  - High thrust, can tailor thrust curve to some extent
  - Low cost
  - Simple and reliable
  - Storable
- Disadvantages:
  - Low performance
  - Safety/Toxic combustion products
  - Extremely hard to throttle
  - Thrust is propellant temperature dependent
  - Cracks can lead to burn throughs or explosions
  - Can’t stop combustion once its started

# Solid Rocket Motor




K: Empirical constant
$T_1$: Empirical propellant detonation temperature
n: Empirical exponent

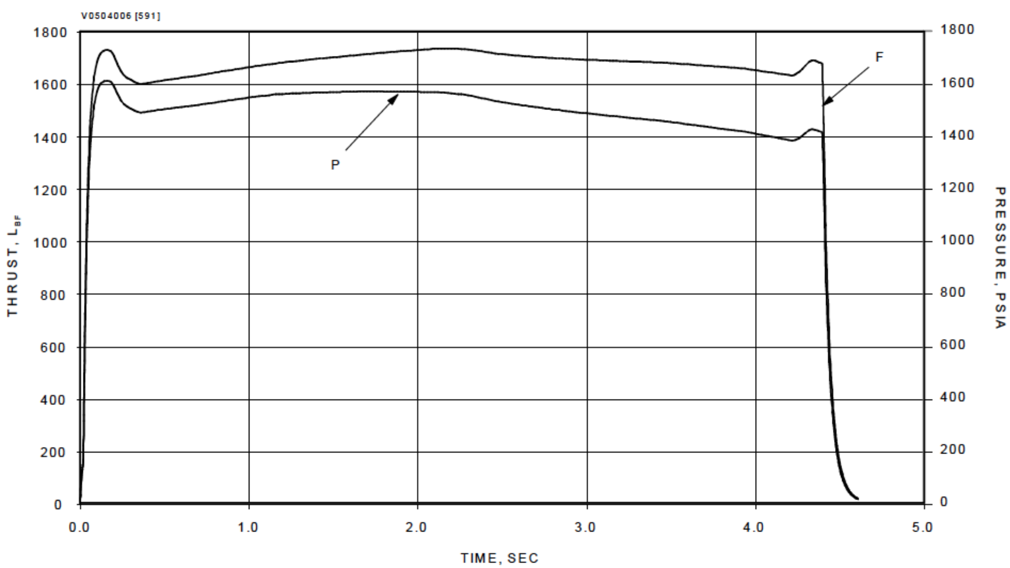
Regression rate is pressure and temperature dependent

$$\rho_p A_b \dot{r} = \frac{d}{dt}(\rho_c V_c) + \frac{A_t P_c}{C^*}$$

$$\dot{r} = \frac{K}{\underbrace{T_1 - T_p}}(P_c)^n$$

Often written as a, an empirical constant that depends on temperature

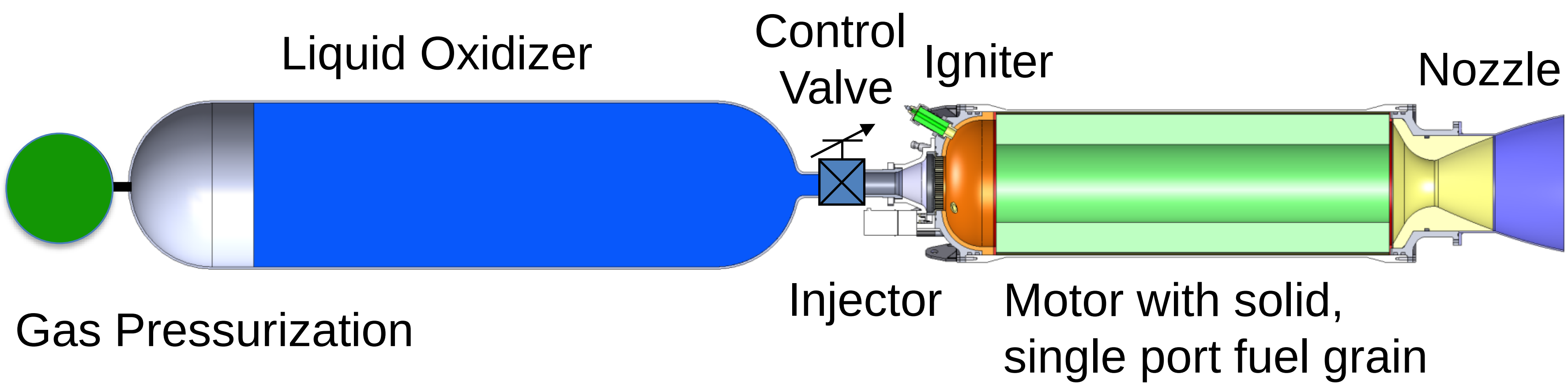
# Example: Orbital ATK's Star 8 Motor




Three of these Rocket Assisted Descent (RAD) motors were used to land Spirit and Opportunity on Mars

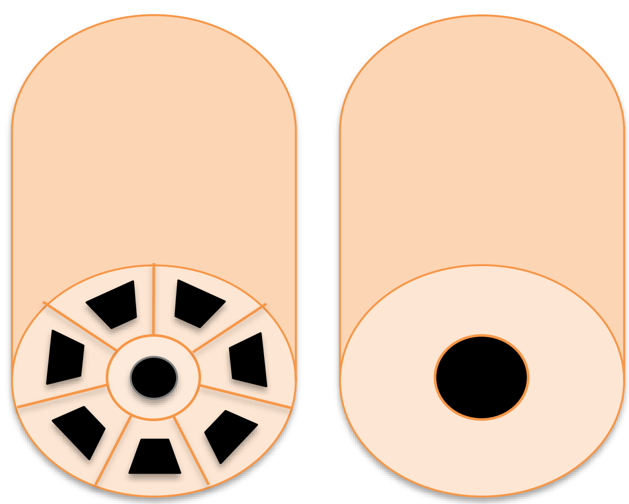
| | |
|---|---|
| **MOTOR DIMENSIONS** | |
| Motor diameter, in. | 8.06 |
| Motor length, in. | 27.07 |
| **MOTOR PERFORMANCE (-22°F VACUUM)** | |
| Burn time/action time, sec | 4.33/4.51 |
| Ignition delay time, sec | 0.025 |
| Burn time average chamber pressure, psia | 1,500 |
| Maximum chamber pressure, psia | 1,572 |
| Total impulse, lbf-sec | 7,430 |
| Propellant specific impulse, lbf-sec/lbm | 274.0 |
| Effective specific impulse, lbf-sec/lbm | 272.9 |
| Burn time average thrust, lbf | 1,681 |
| Maximum thrust, lbf | 1,742 |
| **NOZZLE** | |
| Initial throat diameter, in. | 0.879 |
| Exit diameter, in. | 4.095 |
| Expansion ratio, initial | 21.7:1 |
| Cant angle, deg | 17 |
| **WEIGHTS, LBM** | |
| Total loaded | 38.43 |
| Propellant | 27.12 |
| Case assembly | 6.12 |
| Nozzle assembly | 3.69 |
| Total inert | 11.31 |
| Burnout | 11.20 |
| Propellant mass fraction | 0.71 |
| **TEMPERATURE LIMITS** | |
| Operation | -40º-104°F |
| Storage | -65º-140°F |
| **PROPELLANT DESIGNATION** | TP-H-3062 |
| **CASE MATERIAL** | Titanium |
| **PRODUCTION STATUS** | Flight-proven |

# Hybrid Rockets




Classical Fuels

- Multi-port (wagon wheel)
- Diffusion limited regression rate
- e.g. HTPB

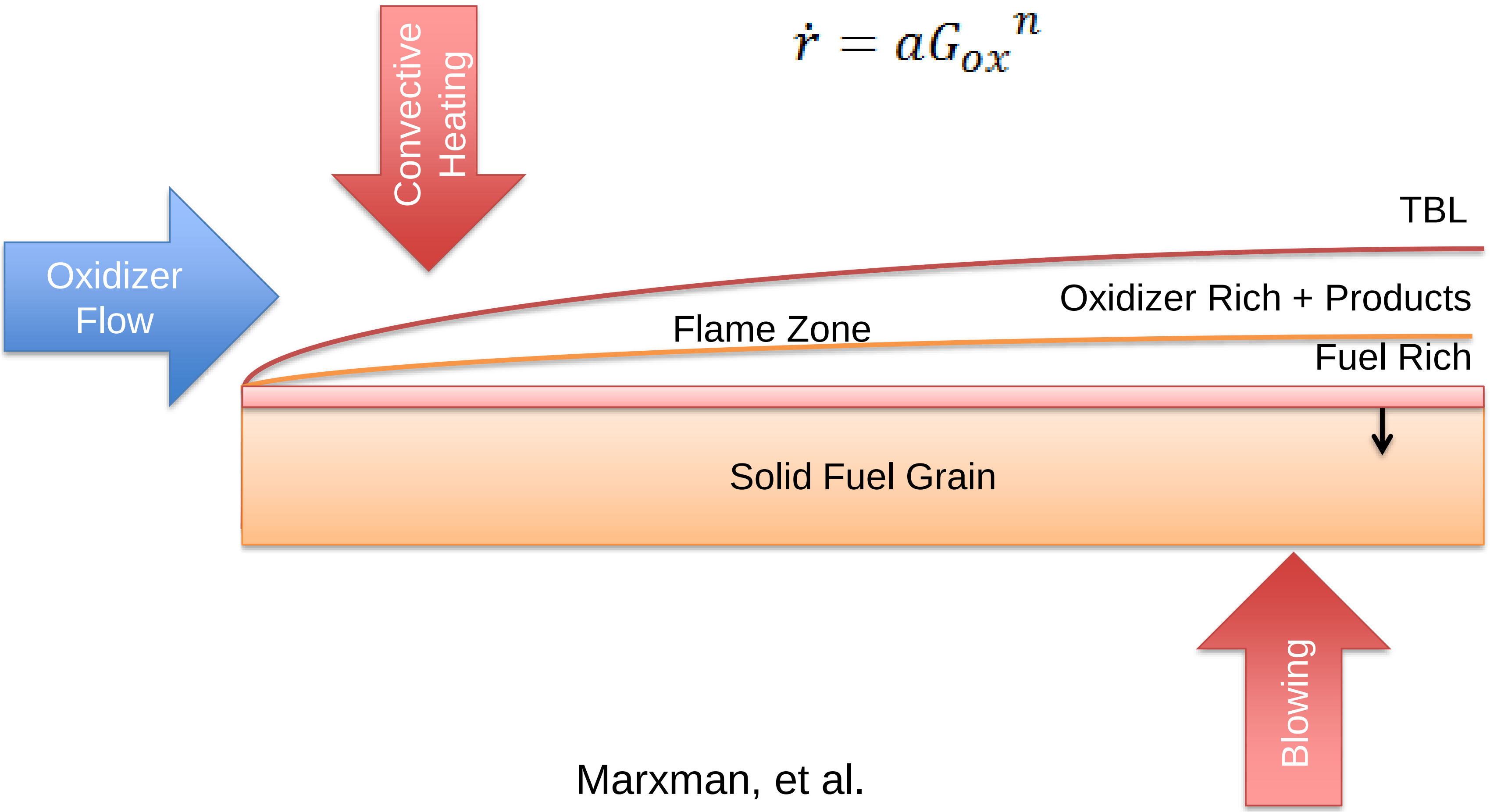


Liquefying Fuels

- Single-port
- High regression rate
- e.g. Paraffin

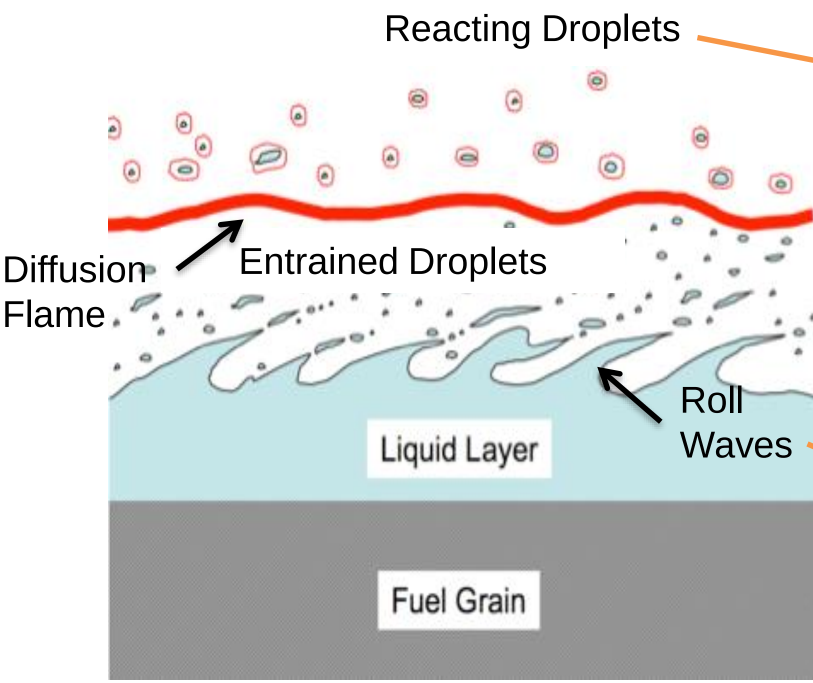
# Classical Hybrid Combustion

$$\dot{r} = aG_{ox}{}^{n}$$

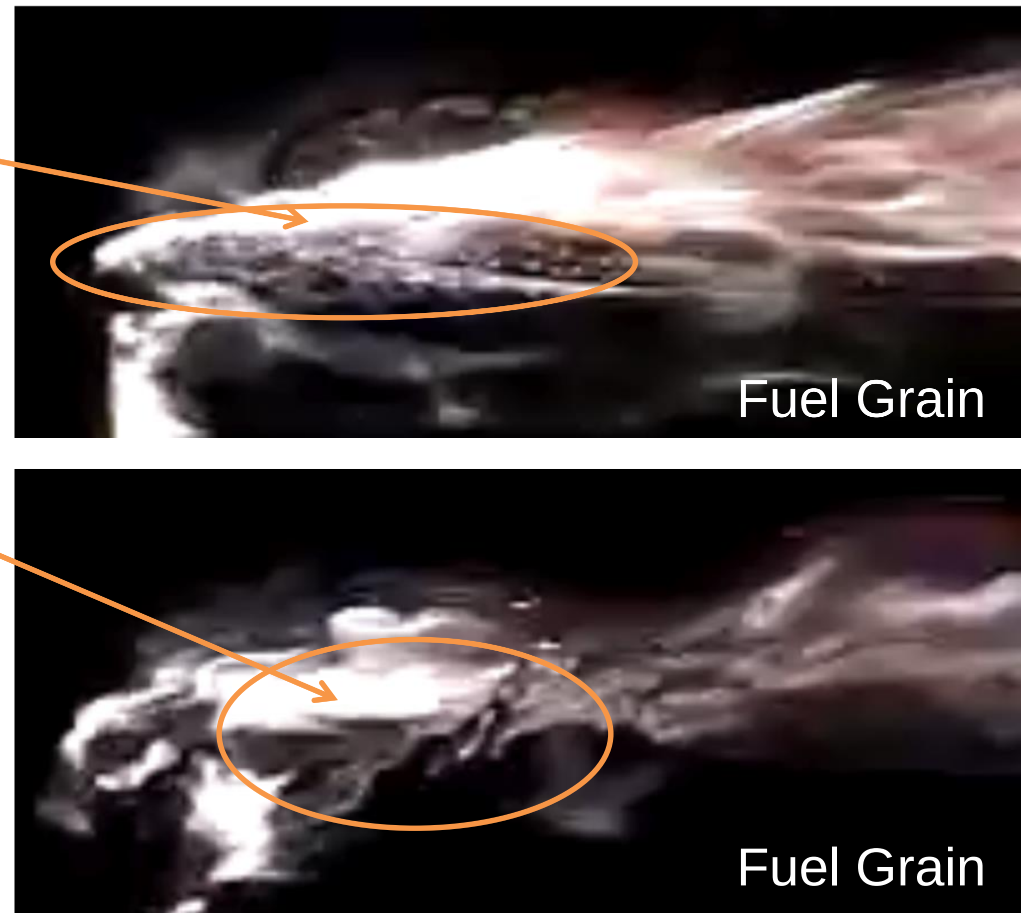



Marxman, et al.

# High Regression Rate Fuels



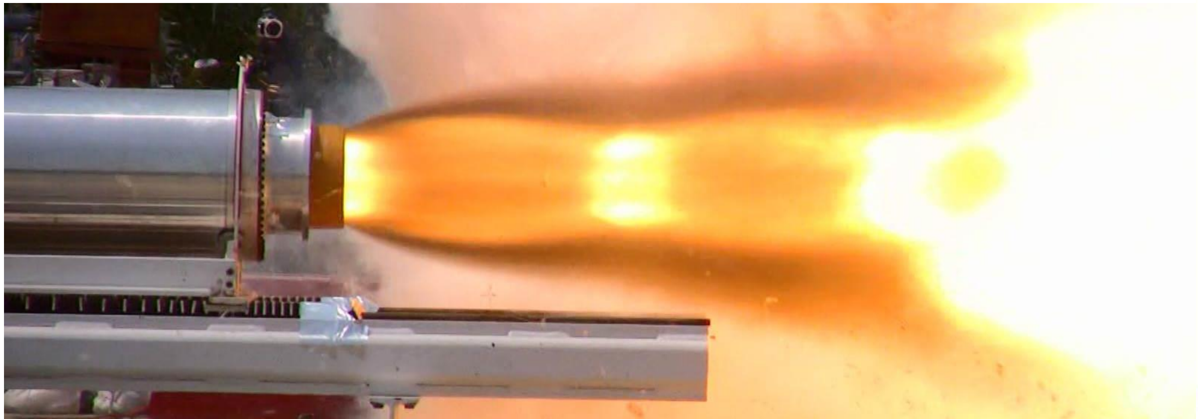

Cantwell, Karabeyoglu, &
Altman, 8th ISICP Cape Town, SA, 2009

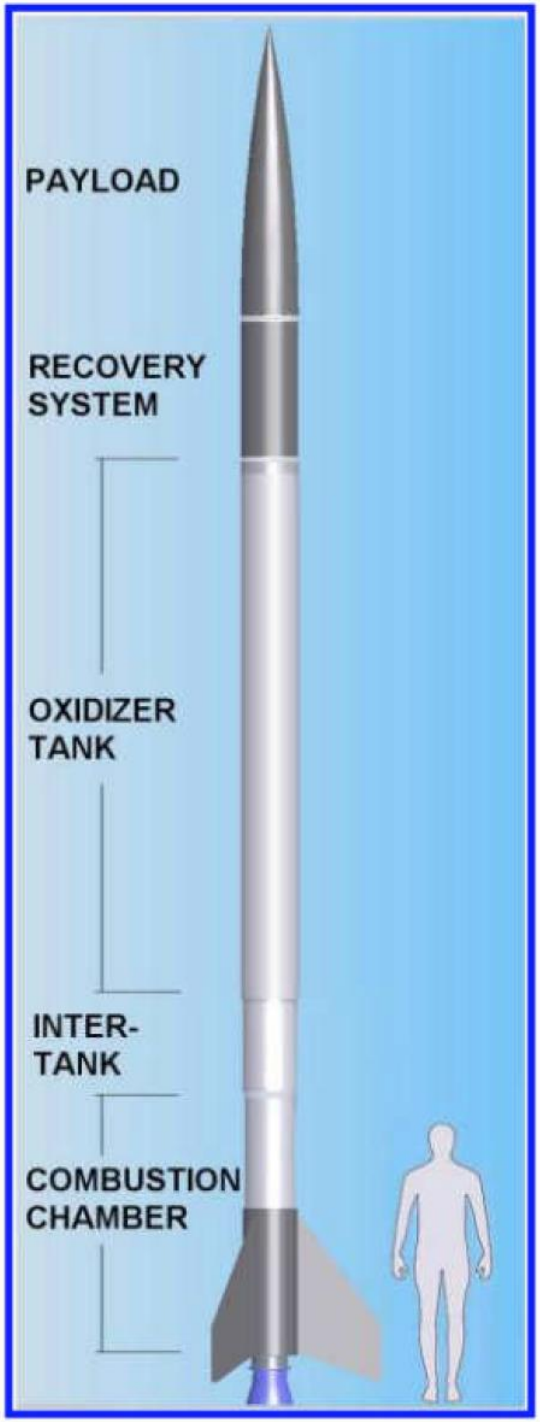



Ashley Chandler, Ph.D. Dissertation, 2012

# Example: Peregrine Sounding Rocket

- Objective: design, build, test, and fly a stable, efficient liquefying fuel hybrid rocket.
- Specs:
  - Paraffin-based fuel with Nitrous Oxide, Earth storable
  - Size: diameter of 15 in. (38.1 cm)
  - Thrust: 14,000-lb (62.3-kN)
- Check out one of the hotfire tests at NASA Ames.





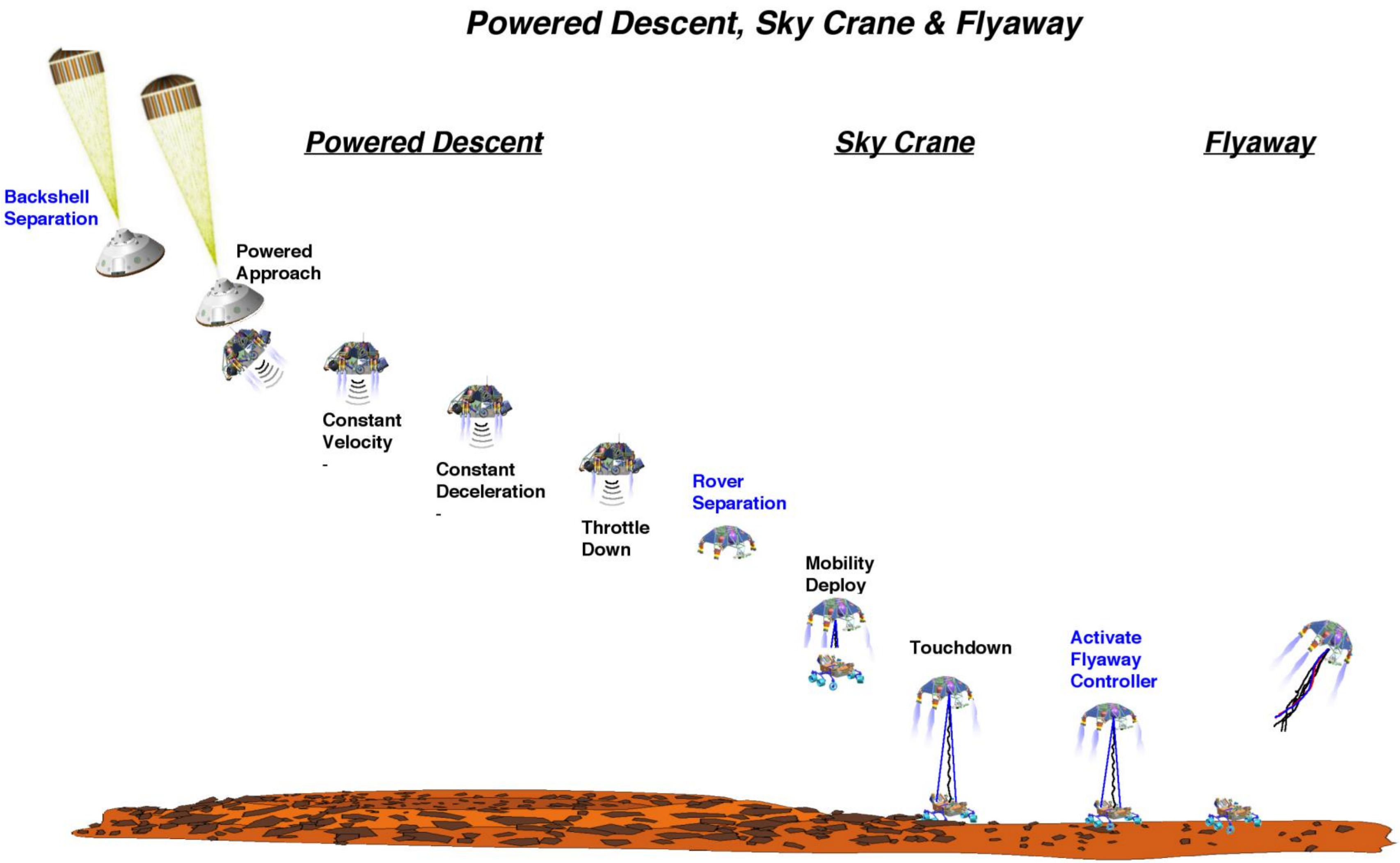
# Propulsion Summary

| | | Hybrid ($Paraffin/GO_2$) | Solid | Liquid (MMH/NTO) | Monoprop |
|---|---|---|---|---|---|
| Isp (Performance) | | 330 s | 285 s | 324 s | 240 s |
| Restart capability | | Yes, multiple | N/A | Yes, multiple | Yes, multiple |
| Throttling | | Simple, 10:1 | None | Complex, 3:1 | Simple, 10:1 |
| Low temperature storage and operations | | < -90 C (Predicted) | - 40 C | +13 C | + 13 C |
| L/D Ratio | | High | Low | Moderate | Moderate |
| Safety | Toxicity | Nontoxic | Toxic | Toxic | Toxic |
| | System Complexity | Moderate | Low | High | Moderate |
| | Recurring Cost | Low | Low | High | Moderate |

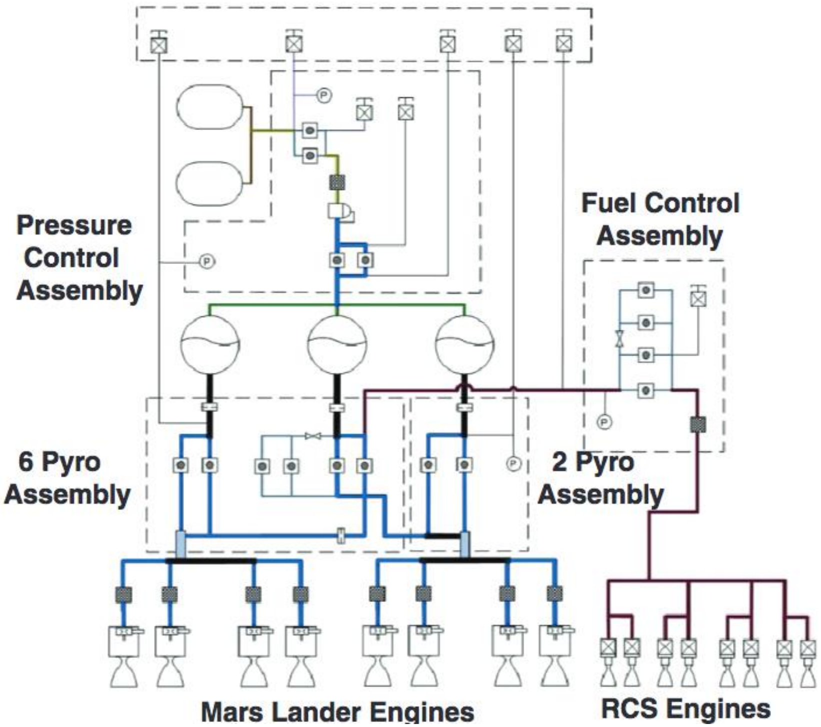
# Spacecraft Systems

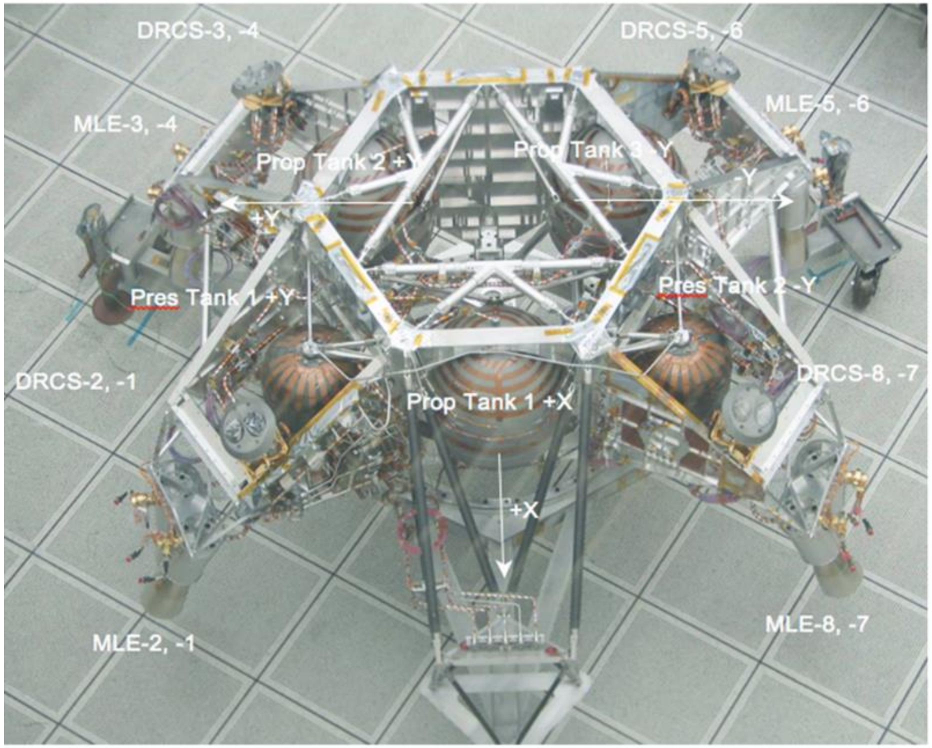
- Propulsion system: you need more than a thruster, engine, or motor to get to (or around in) space.
  - Feed system for monoprops, liquid biprops and hybrids
  - Attitude Control System (ACS)/Reaction Control System (RCS)
  - Ignition if not catalytic or hypergolic
- Support structure
- Avionics/Telecom
- Payload

# MSL: Seven Minutes of Terror



# MSL Descent Stage



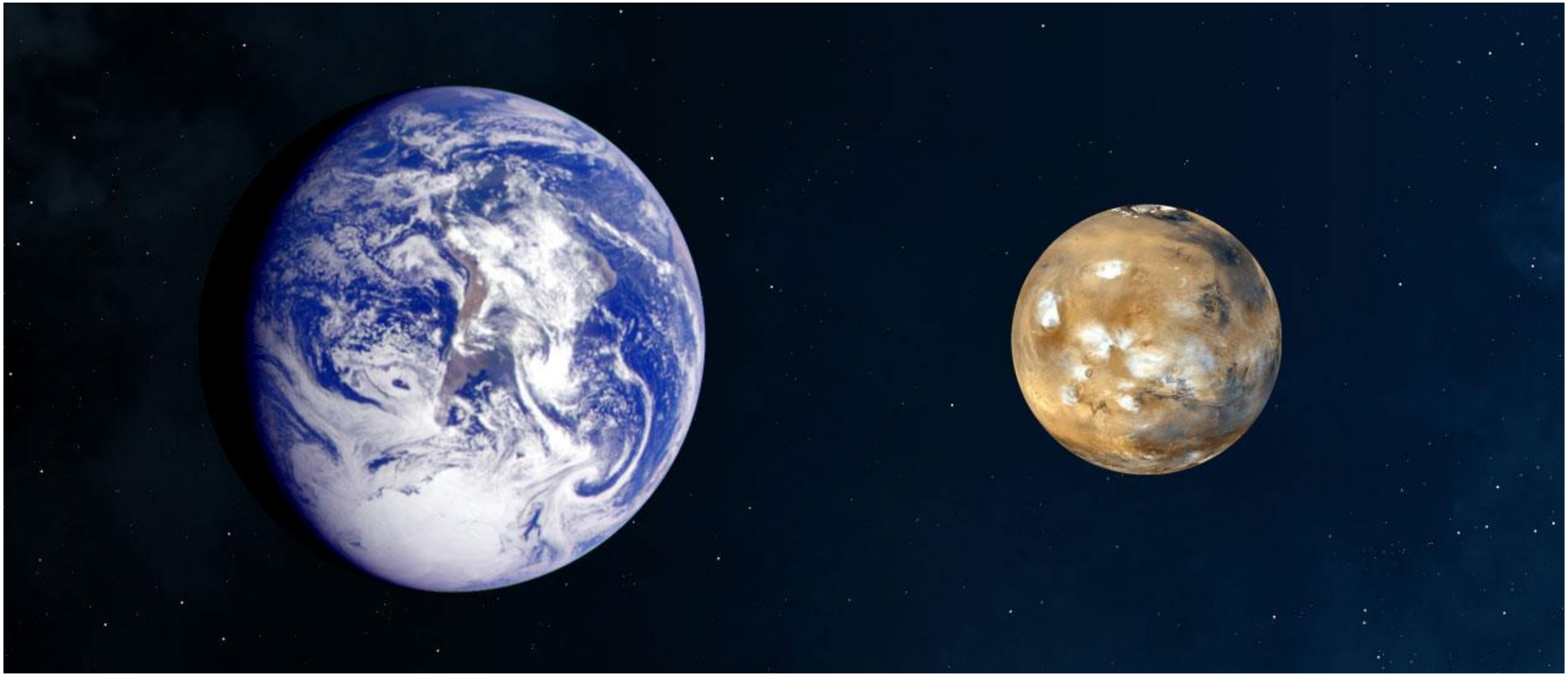




Baker et al., Journal of Spacecraft and Rockets, Vol. 51, No. 4 (2014), pp. 1217-1226.

# Testing

- Acceptance vs. Qualification (vs. Protoflight)
- Functional/performance
- Proof and leak
- Environmental

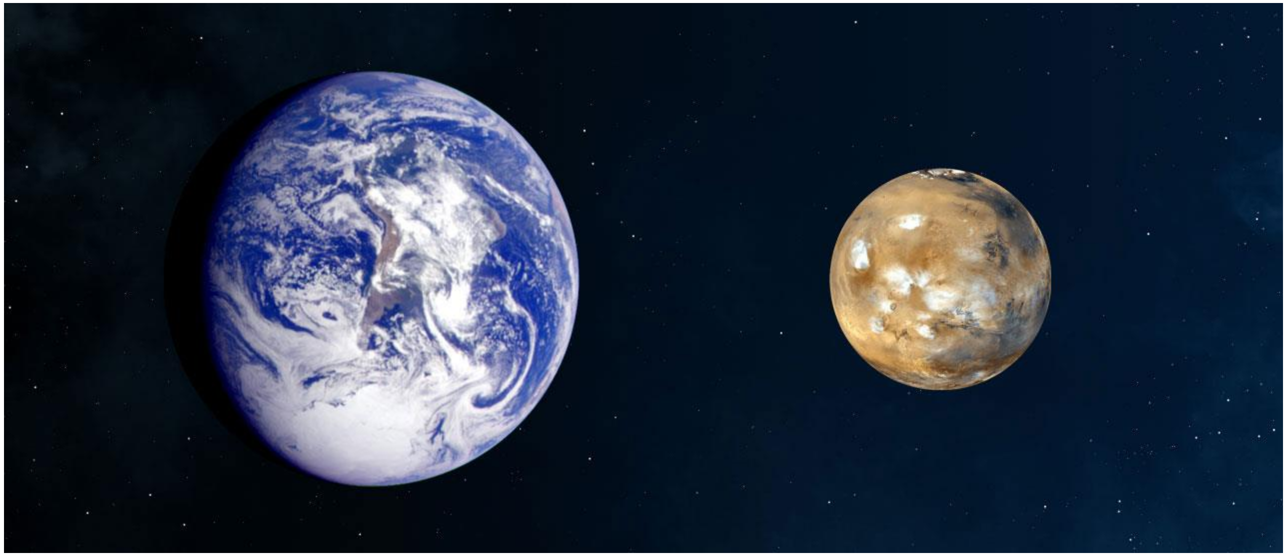
# Environments to Survive



Source: NASA

# Environments to Survive

- Earth
  - Shipping to the launch site
  - Rocket launch
- Cruise
  - Inside aeroshell
- Entry Descent and Landing
  - Aerobreaking
  - Parachute
  - Divert Maneuver
  - Skycrane
- Mars Surface



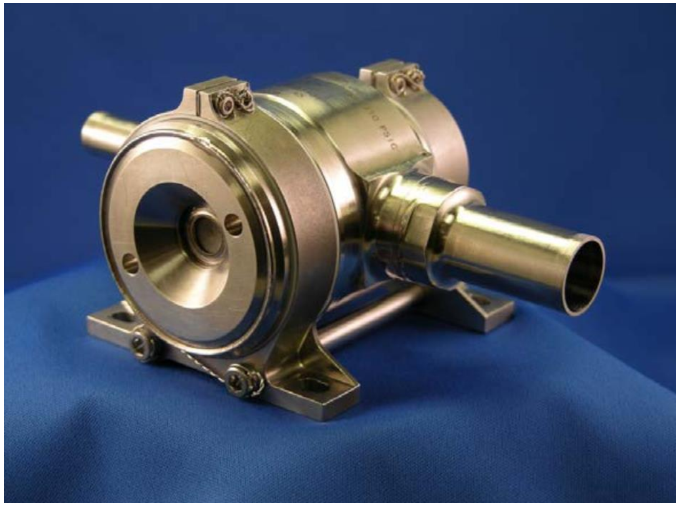
Source: NASA

# Types of Environments & Examples

- Thermal
  - Natural environment (max temperature is often at the Cape for launch, min on Mars can be <-100C)
  - Planetary Protection bake out
- Radiation (Mars: 8 rad/year per Mars Oddssey on average)
- Forces/accelerations – rockets, parachutes, etc.
- Random Vibration
- Pyroshock

# Example: M2020/MSL Regulator

- Modified for M2020/MSL from Shuttle
  - This hardware had already flown on shuttle and was modified for this application
- Acceptance and delta-qualification testing were conducted
  - Flow cycles, flow performance mapping, hot and cold inlet gases, hot and cold thermal environments, solenoid valve slam starts, representative mission profiles, and flow mapping.
  - Pyrovalve shock
  - Random vibration



Mizukami, et al. “Space Shuttle 750 psi helium regulator application on Mars Science Laboratory propulsion.” AIAA Joint Propulsion Conference, Denver, Colorado, August 3-5, 2009

Questions?


Image: NASA